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Dockless bike-sharing's impact on mode substitution and influential factors: Evidence from Beijing, China

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Abstract: As a newly emerged bike-sharing system, dockless bike-sharing has the potential to positively influence urban mobility by encouraging active cycling and drawing users from car, public transit and walking. However, scant empirical research explores the extent to which dockless bike-sharing replaces other travel modes for different travel purposes. There is a lack of knowledge about how dockless bike-sharing users' personal characteristics and neighborhood environment features influence their mode substitution behaviors. Using survey data collected from residents in Beijing and geodata of land use and public transit, we conduct four multinomial logistic models to explore potential mode-substitution behaviors influenced by dockless bike-sharing for four travel purposes: work or education commuting, sports and leisure, grocery shopping, and recreational activities such as shopping, eating and drinking. The results indicate that, for the majority of respondents, dockless bike-sharing systems potentially substitute for walking or public transit. In addition, our analysis of travel attitudes points out that dockless bike-sharing not only attracts bicycle lovers but also users with a preference or positive attitude toward other travel modes. The positive association between the length of bicycle paths and the likelihood of potentially replacing public transit or motorized vehicles by dockless bike-sharing also reveals that the cycling infrastructure of residential neighborhood could be an important facilitator for users of public transit and motorized vehicles to switch to dockless bike-sharing systems.

Keywords: Dockless bike-sharing, mode substitution, active travel, built environment, shared mobility

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1 Introduction

Technological innovation has been gradually incorporated into new, shared, and often dockless micromobility systems. Benefitting from the technological innovations of digitalized payment systems and GPS (global positioning system) location tracking, dockless bike-sharing is becoming increasingly

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introduced in many cities around the world. This new mode is often introduced in cities with the goal of encouraging local populations to improve their health by participating in active cycling as well as improving first- and last-mile connections for public transport. As a symbol of the fourth generation of bike-sharing systems, dockless bike-sharing potentially increases the flexibility and freedom as compared to traditional docked systems in terms of bicycle accessibility (Chen, van Lierop, & Ettema, 2020a). The traditional docked systems, usually identified as the third generation of bike-sharing systems, originated from the "white bikes" for free use in Amsterdam which then developed into a second generation of coin-deposit shared bikes first introduced in Copenhagen in the 1990s (DeMaio, 2009; Shaheen et al., 2010). The third generation docked systems are usually IT-based, involve credit card payments and feature system integration (e.g., a smart card integrated with public transit) (Shaheen et al., 2010). In contrast to earlier generations, the fourth generation is characterized by the inclusion of an embedded GPS, used to locate the bicycles, which corresponds to a smartphone application to lock and unlock a bicycle and is easily accessed using cashless online payment. Riders are able to end their trips at any time or place in either geofenced and designated parking areas or public spaces where bicycle parking is allowed. The dockless model introduces users with high flexibility but also additional uncertainty in accessing dockless bikes at locations where the users have dropped off the bikes (Peters & MacKenzie, 2019). In addition, the deregulated nature of dockless models has triggered irregular parking behavior among a non-negligible number of users, leading to negative impacts such as violating pedestrian rights, blocking cycle paths and sidewalks, and hindering the flows of metro users due to parked bicycles accumulating at station entrances and exits (Kutela et al., 2021; Liu et al., 2020).

Various aspects of dockless bike-sharing systems have recently been studied, such as system usage (Lin et al., 2019; Shen et al., 2018), user profiles (Du & Cheng, 2018), accessibility and distribution of bicycles (Ai, Li, Gan, et al., 2018; Mooney et al., 2019) and the implications of such systems for urban mobility (Li et al., 2019). Still, there is uncertainty about how dockless bike-sharing contributes to (possible) mode substitution. Potential advantages of dockless bike-sharing systems, such as increasing physical activity and improving an individual's overall well-being, increasing sustainable active transportation at the city level, and reducing greenhouse gas emissions and fuel use at the national level (Chen, Liu, et al., 2020; Lin et al., 2019; Zhang & Mi, 2018) assume that a significant proportion of dockless bike-sharing journeys are replacing trips previously made by car and public transport. Likewise, the introduction of dockless bike-sharing systems in cities may result in new trips being generated, but additional research is needed to understand this further. International evidence has indicated that traditional docked bike-sharing systems mainly substitute for active travel or public transit trips, and the degree to which car use is being substituted displays an inconsistent pattern (e.g., Fishman et al., 2014, 2015; Kong et al., 2020; Zhu et al., 2013). To what extent findings from docked bike-sharing studies on mode substitution apply to dockless bike-sharing remains unexplored. In addition, although increasing evidence has revealed that individuals' socio-demographics, attitudes, and built environment often influence how, when, and where dockless bike-sharing systems are used (e.g., Guo & He, 2020; Ni & Chen, 2020), there is a lack of knowledge about how these factors relate to the mode that is substituted for. Finally, it is unclear what role varying travel purposes, such as commuting or traveling for leisure, play in mode substitution patterns of dockless bike-sharing.

This present paper seeks to understand to what extent the use of dockless bike-sharing systems potentially substitutes for car use, public transit, or other forms of active modes. Using a quantitative approach, we explore how individuals' socio-demographics, travel-related attitudes, and residential neighborhood built environment are related to mode substitution by dockless bike-sharing. In addition, we investigate how the mode substitution behaviors by dockless bike-sharing vary among different types of travel purposes, such as work or education commuting, leisure, and grocery shopping. Understanding how and to what extent dockless bike-sharing systems affect individuals' utilization of other transport modes can provide insights into the environmental and health impacts brought by the pervasion of dockless bike-sharing systems.

The remainder of this paper is organized as follows. In the next section, we present the literature on mode substitution in relation to dockless bike-sharing and construct the theoretical framework for empirical analysis. Next, we introduce the study context and data collection process. Subsequent sections highlight the methodology and present the analysis and results. The final section presents a discussion of the empirical outcomes, conclusions, and unresolved issues as a guide for future research.

2 Literature review

Mode substitution occurs when individuals use a travel mode to make a journey that was previously made using another mode. Increasing international research has been conducted on mode substitution in the context of docked bike-sharing. However, few studies have focused on the mode substitution of dockless bike-sharing systems. This section will begin by presenting the existing studies about traditional docked bike-sharing systems, which is then followed by a discussion of distinctive characteristics of dockless bike-sharing compared to docked bike-sharing. Accordingly, we develop hypotheses for the mode substitution implications of dockless bike-sharing and summarize the theoretical framework for our empirical analysis.

2.1 Mode substitution for docked bike-sharing

International evidence has suggested that the implementation of docked bike-sharing systems potentially draws users away from public transit and other forms of active travel (Kong et al., 2020; Ma et al., 2020; Martin & Shaheen, 2014). Fishman et al. (2015) summarized the results of an online survey that asked, "Thinking about your last journey on bikeshare, which mode of transport would you have taken had it not existed?" (Fishman et al., 2015, p. 137), across the members of five docked bike-sharing programs in the United States, England and Australia. Users indicated that their current trips taken by docked bike-sharing were most often substituting trips pervious made using public transit and walking. A more recent study by Campbell and Brakewood (2017) concluded that in Manhattan and Brooklyn, for every thousand bike-sharing docks along bus routes, a 2.42% decline in unlinked (that is, passengers are counted each time they board vehicles) bus trips on routes tended to appear. Shaheen et al. (2013) suggested evaluating the trip purpose for which mode substitution occurred, as substitution patterns may differ by purpose. Empirical evidence of such differentiation, however, is lacking.

The mode substitution for walking and the use of private bicycles often takes place in first-/last-mile trips and trip chain connections. By comparing the mode choice decision for the first-/last-mile trips before and after the advent of docked bike-sharing, Fan et al. (2019) found that most first-/last-mile trips currently taken by docked bike-sharing were previously made by walking or private bicycles. In addition, in a study of PBS (public bikeshare scheme) riders in Shanghai, Zhu et al. (2013) revealed that a substantial proportion of PBS users shifted from public transit, walking and private bicycles, and 47.3% of docked bike-sharing trips in the trip chains were reported to substitute for walking. Evidence suggests that the time- and energy-saving benefits of docked bike-sharing are the main motivations for individuals to use docked bike-sharing to replace walking (Shaheen et al., 2013). Moreover, the flexibility and accessibility of bike-sharing systems could provide a solution for private bicycle users to the issue of theft and the inconvenience of carrying bicycles through entire trip chains, thereby drawing individuals away from private bicycles (Fan et al., 2019; Fuller et al., 2013).

Compared to traveling by public transit and walking, the capability of docked bike-sharing systems to reduce car usage is inconsistent according to different contexts. Research from China indicated a low mode substitution from cars to docked bike-sharing. For example, Tang et al. (2011) recorded that docked bike-sharing only substituted for 5.2%, 4% and 0.46% of total car trips in Beijing, Shanghai, and Hangzhou, respectively. These results resemble what Fishman et al. (2014) found in their study of commute transport patterns for Washington, D.C., and London, with 7% and 2% of docked bike-sharing users, respectively, replacing trips that previously would have been made by car throughout 2012. In contrast, the same study found that the docked bike-sharing programs in Brisbane, Melbourne and Minneapolis display relatively high rates of car mode substitution for travel to work in 2012, recording substitution rates of 19%, 21% and 19%, respectively, in these three cities. To explain the inconsistency among the car substitution rates of these cities, Fishman et al. (2014) revealed a positive correlation between commuting car usage and the rates at which docked bike-sharing substituted for car usage. As the population density in Washington, D.C., and London is much higher than that in the other three cities, car usage was often seen as being inconvenient. Therefore, people who had the opportunity to choose an alternative mode, often had done so. And it becomes more difficult for docked bike-sharing to draw users away from car.

2.2 Determinants of mode substitution

The mode substitution dynamics in response to docked bike-sharing systems have been explored as a function of individual and spatial attributes. Barbour et al. (2019) conducted a survey among the registered users of CycleHop Bike Share Company and found that younger individuals and those with a lower annual household income were more likely to make car trips in the absence of bike-sharing. Shaheen et al. (2013) revealed in their study of four docked bike-sharing systems located in Montreal, Toronto, the Twin Cities, and Washington, D.C., that increased age, being male and living in lower-density areas were the common features across the surveyed cities influencing the substitution of docked bike-sharing for public transport. With regard to health status, Barbour et al. (2019) suggested no significant influence of self-reported health factors on the likelihood of docked bike-sharing users using the bike-sharing trips to replace car trips. Yet, they found that 72.7% of people who were considered obese (based on their body mass index) were more willing to switch to car trips in the absence of docked bike-sharing, and 27.3% suggested less willingly.

Apart from socio-demographics and personal characteristics, psychological factors may also play a role in mode substitution patterns in response to dockless bike-sharing. Mode-specific attitudes have been reported to have strong effects on individuals' intention to take the corresponding travel mode (Heinen et al., 2011). Other types of travel-related attitudes, such as an awareness of environmental concerns discourages the auto use (Anable, 2005), also a positive attitude towards travelling itself encourages the use of modes with longer trip durations (De Vos, 2018). Therefore, it can be speculated that travel-related attitudes could also affect substitution patterns in the context of dockless bike-sharing. However, there haven't been many studies on psychological determinants of mode substitution by docked bike-sharing. In a study of docked bike-sharing systems in Nanjing, China, Yang et al. (2016) found that the combined use of a docked bike-sharing system and public transit were more likely to attract users from male motorists who were lower-level employees and those who reported experiencing unpleasant commute journeys.

With regard to the spatial effects on the mode substitution of docked bike-sharing, Martin and Shaheen (2014) and Shaheen et al. (2014) found in a study of several North American cities that sub-

[1] A 750m buffer effectively covers the majority of the upper east side area and the adjacent existing metro line. Additionally, it excludes the properties directly located at the edge of the Central Park, which can maintain price premium from the view to the park that we have no variables to control for.

stitution of public transport by bike-sharing was more likely to occur in larger and denser cities, whereas docked bike-sharing tended to be more complementary as a first-/last-mile connection to public transit in smaller or median-sized and less dense cities. For environmental factors such as mode accessibility, Barbour et al. (2019)'s study found that individuals who have a higher vehicle ownership in their households, and individuals who reported a short time (less than 3 minutes) on finding a parking spot during their most regular trips were less likely to use docked bike-sharing to substitute for car trips.

2.3 Dockless bike-sharing and potential mode substitution

Although there are similarities between docked and dockless bike-sharing systems, dockless bike-sharing offers the advantage of higher flexibility with regard to starting, and especially ending trips. Dockless shared bicycles are often located where the previous users drop them off. Similar to docked bike-sharing, users still need to walk out to obtain bicycles. However, the no-docking design allows users to end their journey directly at their final destination. As the connection of traditional docked systems with public transit relies largely on the number of docks available, the pressure of drop-off restriction and space limitation around public transit stations is lower in a dockless system. In addition, dockless bike-sharing systems are often operated with a greater number of shared bikes than docked bike-sharing due to a lower requirement of economic and human resource input for docking stations (Mooney et al., 2019), which enables a larger availability of shared bicycles surrounding public transit stations (Mobike Global, Beijing Tsinghua Tongheng Planning and Design Institute, & China New Urbanization Research Institute, 2017). The improved experience at the end of rides and the higher availability of dockless shared bicycles can contribute to tighter integration with public transit, offering dockless bike-sharing as a "first-/last-mile" trip option and meanwhile complementing the walking transfers in-between public transits (Ai, Li, & Gan, 2018). Therefore, individuals are encouraged to replace walking and private bikes with dockless bike-sharing for short-distance access or egress travel. Additionally, tighter integration enables a highly flexible trip chain of dockless bike-sharing and public transit that is more competitive with car transportation and may therefore substitute for car trips.

Recently, the emergence of dockless bike-sharing systems has induced increasing research about their impact on mode substitution. Ma et al. (2019) conducted a survey among car drivers in Nanjing and revealed that two-thirds of car drivers are willing to use dockless bike-sharing for trips shorter than 2 km. The Mobike white paper report released on April 12, 2017 suggests that the proportion of private car trips had decreased by approximately 3.2% within one year since the emergence of dockless bike-sharing systems. Mobike users in China who participated in the survey reported that their trips via illegal autorickshaw had been reduced by more than 50% (Mobike Global et al., 2017). Another study by Ma et al. (2020) investigated the modal shift dynamics caused by different kinds of bike-sharing systems, including dockless bike-sharing (Mobike) in Delft, the Netherlands. Thirty-seven percent of the Mobike users reported a reduction in their private car/passenger and taxi usage. One-third of Mobike users had reduced their private bicycle usage, while only 16% of Mobike users claimed they used buses or trams more than before, probably due to more convenient access and egress to bus/tram stations. Mode substitution regarding commuting was also explored in this study, and the results revealed that the percentage of Mobike users shifting from private bicycles and walking after the introduction of Mobike accounted respectively for 20.48% and 7.23% of the total number.

Previous literature has concentrated primarily on the impacts of docked bike-sharing systems on mode substitution in general. This summary of the available literature revealed a general pattern in which docked bike-sharing attracts users largely from public transit and walking while reducing car usage to a limited extent. Nonetheless, the limited empirical exploration on the effect of dockless bike-sharing systems on mode substitution leaves us with the question of whether such impacts display a pattern consistent with that of docked bike-sharing. Moreover, there is a lack of studies about the underlying factors associated with dockless bike-sharing users' mode substitution behaviors and whether trip purposes play a role in the mode substitution dynamics of dockless bike-sharing.

This study examines the mode substitution impacts of dockless bike-sharing and the effects of individual characteristics and built environment on dockless bike-sharing users' mode substitution behaviors for different travel purposes in Beijing. Individual characteristics that have been accounted for in our investigation include individuals' sociodemographic characteristics, social environment, and travel attitudes. Built environment attributes consider mode accessibility, neighborhood road network and neighborhood satisfaction. The impacts of dockless bike-sharing on mode substitution were examined for the following four travel purposes: work or education commuting, sports and leisure, grocery shopping, and recreational activities such as shopping, eating and drinking.

3 Study area, data, and methodology

3.1 Study area

Our study area, the city of Beijing, China, is a megacity with a population of 21.5 million (as of the end of 2018). The dominant travel mode in Beijing is public transport (including metros and buses), which accounted for 46% of all trips in 2018 (Beijing Transport Research Center, 2019). The first dockless bike-sharing system was introduced in June 2015 on the Peking University campus for students' convenience but expanded to other areas of Beijing soon afterwards and subsequently to other major cities in China. In 2017, the number of registered users in Beijing was close to 11 million, accounting for nearly half of the city's population (Beijing Municipal Commission of Transport, 2018). As the oversupply and deregulated nature of dockless shared bikes resulted in negative impacts such as violating pedestrian rights and blocking cycle paths (Chang et al., 2018; Shi et al., 2018), the volume of operating shared bikes was restricted by the city government to a total of 1.91 million bicycles from nine operators in August 2018. Nevertheless, the average number of rides per day reached 1.42 million in Beijing in 2018 (Beijing Municipal Commission of Transport, 2018).

3.2 Sample and data measurement

An online survey containing questions about individuals' sociodemographics, travel attitudes, satisfaction, and travel behavior—including users' mode substitution choices for dockless bike-sharing rides—was conducted among residents of Beijing, China. We hired a recruitment company in China (www.wjx.cn) to recruit potential participants by emailing questionnaires to Beijing residents aged 16 and older from the recruitment company's large online survey panel with 2.6 million members in China. Individuals under age 16 are not allowed to register or use the dockless bike-sharing systems and hence were not included in the survey. The data collection process was completed between August 7, 2018, and November 31, 2018. A total of 606 valid questionnaires were received from the respondents, with a response rate of 6.44%. Of the 606 individuals who responded to the questionnaire, 489 were from dockless bike-sharing users. Our study seeks to explore the potential mode substitution behavior in response to dockless bike-sharing systems. Hence, the current study only included 489 questionnaires from dockless bike-sharing users in the analysis. The spatial variables of built environment were derived from the land-use dataset of China, including the road networks from OpenStreetMap (OSM) updated in September 2018 and the public transit dataset of Beijing in November 2017 compiled by the Urban Data Party (www.udparty.com).

The participants' sociodemographics and neighborhood environmental characteristics are shown in Table 1. A wide range of dockless bike-sharing users aged between 17 and 61 with a balanced gender distribution was included in the research sample, but individuals aged 16 to 30 accounted for 61% of the participants. Full-time employees and people with at least a bachelor's degree were the main contributors to this sample. Nearly half of the participants reported living in privately owned places. Individuals with low, median, and high household incomes were represented in relatively equal proportions. For mode accessibility, the majority of the participants owned at least a car in their household, whereas one-third reported having at least an e-bike, and half reported owning at least a bicycle. With regard to dockless bike-sharing users' travel purposes, the majority (72.39%) of the research sample would turn to dockless bike-sharing for their work or education commuting travel. Slightly over half of the participants, however, indicated using dockless bike-sharing in their trips for sports and leisure, grocery shopping, or recreational activities such as shopping, eating and drinking.

Table 1. Sample characteristics (N = 489)

Variables	Definitions	Mean (Std. Dev.)	No.	Pct. (%)
Individual attributes				
Age (years)	17-30		299	61.1
	31-45		164	33.6
	46-61		26	5.3
Gender	Female		249	50.9
	Male		240	49.1
Education	High school/secondary technical school and below		18	3.7
	University/college bachelor's degree		355	72.6
	Master's degree and above		116	23.7
Household income (monthly)	Low income (less than 12000 yuan)		144	29.4
	Median income (12000 - 20000 yuan)		187	38.2
	High income (more than 20000 yuan)		158	32.3
Employment	Full-time employed		364	74.4
	Part-time employment, students, etc.		125	25.6
Living situation	Privately owned		238	48.7
	Employers' offer/student dormitory		97	19.8
	Others		154	31.5
Self-reported health	Poor and fair		172	35.2
	Good		173	35.4
	Very good and excellent		144	29.4
Social environment		3.83 (0.63)		
Spatial attributes				
Car ownership			359	73.4
Motorcycle ownership			65	13.3
E-bike ownership			162	33.1
Bicycle ownership			248	50.7

Variables	Definitions	Mean (Std. Dev.)	No.	Pct. (%)
The length of bicycle paths within the neighborhood (km)		3.42 (2.65)		
The length of pedestrian-priority roads within the neighborhood (km)		3.97 (3.13)		
Neighborhood satisfaction	Very unsatisfied		3	0.6
	Unsatisfied		30	6.1
	Neutral		206	42.1
	Satisfied		223	45.6
	Very satisfied		27	5.5
Dockless bike-sharing users' travel purposes				
Work or education commuting			354	72.4
Sports and leisure			277	56.7
Grocery shopping			250	51.1
Recreational activities (such as shopping, eating and drinking)			263	53.8
Correlation statistics				
Household income*car ownership *(Pearson chi-square: 38.781 (df = 2); p value = 0.000)*	Low income*yes		83	57.6
	Low income*no		61	42.4
	Median income*yes		135	72.2
	Median income*no		52	27.8
	High income*yes		141	89.2
	High income*no		17	10.8

Individuals' potential mode substitution behavior was derived from the survey question: *"What alternative travel mode would you use for the trip if the dockless bike-sharing system did not exist?"* This survey question was asked for the following four travel purposes of daily activities: work or education commuting; sports and leisure; grocery shopping; and recreational activities such as shopping, eating and drinking. Participants could indicate changes in travel modes, including walking, private bicycles, private e-bikes, motorcycles, public transport, taxis and private cars. An additional response "No, I would not make the trip at all" was provided for participants if they decided not to continue that trip in the absence of dockless bike-sharing systems.

The other components of individuals and spatial attributes, including sociodemographics, travel attitude, mode accessibility, neighborhood road networks, and neighborhood satisfaction, were explored as explanatory variables. Sociodemographic variables, such as age, gender, household income, employment, housing situation, self-reported health, and social environment (regarding dockless bike-sharing), were derived from the survey.

In addition to sociodemographics, we investigated the effect of respondents' travel attitudes on mode substitution. This study adopted a previously established factor analysis that we derived from the same dataset (for details, see: Chen, van Lierop, & Ettema, 2020b). This factor analysis is an exploratory factor analysis that was applied to the original survey questions of respondents' travel attitude to model the potential interrelationships and reduce the numbers of observed variables into fewer dimensions. We conducted a principal component analysis (PCA) with a varimax rotation in SPSS. Eight factors that express individuals' different types of travel attitudes were extracted from the 31 observed variables (see Table 2). These observed variables were obtained from the survey, in which the respondents indicated their extent of agreement with 31 statements related to attitudes towards various travel modes, using a five-point scale from "strongly disagree" to "strongly agree." We considered factor loadings greater than ±0.40 to be more important and acceptable in our analysis (Peterson, 2000), therefore, the rotated factor loading threshold of ±0.4 was determined to identify the importance of an item to a factor and to decide the items used subsequently for factor score calculation. We conducted the KMO and Bartlett's test to identify the suitability of our data for factor analysis. The results reported a value of 0.82 for Kaiser-Meyer-Olkin Measure of Sampling Adequacy, and a significant value (p-value = 0.00) for Bartlett's Test of Sphericity. We examined the McDonald's omega for reliability test. For all 31 items used in our exploratory factor analysis, the McDonald's omega is 0.83. When considering these items as indicators for eight latent factors, the McDonald's omega hierarchical is 0.56, and McDonald's omega total is 0.93. We used the regression method to calculate factor scores. A total of 64.8% of the total variance in the responses was explained by the eight derived types of travel attitudes.

Table 2. Derived factor groups—types of travel attitude

Factor groups	Indicators	Loadings
Pro-car	• I like driving	0.715
	• Without a car, I cannot handle my daily life	0.678
	• Owning a car allows me to do more	0.812
	• Owning a car gives me freedom	0.821
	• I do not have any alternative for car use	0.732
	• A car gives me prestige and status	0.618
Pro-e-bike or e-scooter	• I like riding e-bikes	0.891
	• If possible, I would rather use e-bikes than take public transport	0.911
	• Riding e-bikes can sometimes be easier for me than other modes	0.906
	• I think that traveling by e-bike is safer than all other modes	0.805
Pro-public transport	• I like to use public transport	0.807
	• If possible, I would rather use public transport than driving	0.731
	• Public transport can sometimes be easier for me than other modes	0.784
	• Public transport is unreliable	- 0.532
	• I think that traveling by public transport is safer than all other modes	0.456
Pro-bicycle	• I like cycling	0.834
	• If possible, I would rather cycle than take public transport	0.839
	• Cycling can sometimes be easier for me than other modes	0.843
	• I think that traveling by bicycle is safer than all other modes	0.726
Pro-walking	• I like walking	0.782
	• If possible, I would rather walk than take public transport	0.791
	• Walking can sometimes be easier for me than other modes	0.788
	• I think that traveling by foot is safer than all other modes	0.661
Pro-environment or health	• I am concerned about the environmental impacts of my daily travel	0.770
	• I am willing to change my travel mode if it is good for the environment	0.795
	• I am concerned about the health impacts of my daily travel	0.691
	• The trip to/from work is a useful transition between home and work	0.537
Anti-public transport	• Transferring to other buses or metros is annoying	0.664
	• It bothers me that public transport is too crowded	0.846
Anti-traveling	• Travel time is generally wasted time	0.761
	• I prefer to organize my errands so that I make as few trips as possible	0.712

Note. Adapted from: Chen, van Lierop, and Ettema. (2020b). Exploring dockless bikeshare usage: A case study of Beijing, China. Sustainability, 12, 1238.

The analyzed spatial attributes were from both the survey and our spatial datasets. For mode accessibility, apart from the private car, motorcycle, bicycle and e-bike ownership variables that were generated from the survey data, we considered accessibility to public transport by measuring the total number of bus stops and subway stops within the residential neighborhood. The residential neighborhood was defined as the area within a 600-m radius of the respondents' reported home location according to the requirement of an average distance of 500-600 meters between bus stops in Beijing. Neighborhood road networks were measured by the total length, in kilometers, of bicycle paths and the total length, in kilometers, of pedestrian-priority roads within the neighborhood. Neighborhood satisfaction was a subjectively measured variable related to individuals' satisfaction level with their residential neighborhoods.

Among the explanatory variables of our analysis, individuals' self-report health, social environment and neighborhood satisfaction were measured with Likert scales. Individuals' self-reported health was assessed using a five-point scale from "poor" to "excellent." This scale is a robust predictor of mortality and morbidity (Subramanian et al., 2010) and has been previously applied in transport studies (e.g., Li et al., 2021). We then merged the responses into three new categories for further analysis: "poor and fair," "good," and "very good and excellent." Social environment was measured as the average score of the respondents' extent of agreement with the following five statements adopted from Ma and Dill (2015): (1) Most people who are important to me, for example, my family and friends, think that I should use dockless shared bikes more; (2) Most people who are important to me would support me in using dockless shared bikes more; (3) The people with whom I live ride dockless shared bikes to get to places, such as errands, shopping, and work/school; (4) Many of my friends ride dockless shared bikes to get to places, such as errands, shopping, and work/school; and (5) Many of my coworkers/classmates ride dockless shared bikes to get to work/school. Respondents were asked to rank these statements on a five-point scale from "strongly disagree" to "strongly agree." For neighborhood satisfaction, we used an established single-item question measurement (e.g., Hur et al., 2010; Zhang et al., 2017) that asked respondents to indicate on a five-point scale from "very unsatisfied" to "very satisfied" how satisfied they are with the neighborhood they live in.

3.3 Model specification and approach

In the survey, we assessed which travel modes would be substituted by dockless bike-sharing systems if the entire dockless bike-sharing system would be removed from the urban transport system. In this method, we measure the travel modes that users' current trips taken by dockless bike-sharing were potentially to substitute for. Previous studies have also assessed mode substitution information using this kind of hypothetical question. Fishman et al. (2015) investigated the mode substitution of five docked bike-sharing systems by asking respondents the travel mode that would have taken for to replace their last journey on bike-sharing. Cherry et al. (2016) also modelled the travel modes that would be taken now in the absence of an e-bike to evaluate the influential factors on the dynamics over time of the role e-bikes as a substitute for other modes. Although it is noted that people may not always fall back to their previous travel mode choices if the current mode becomes unavailable, we used the measured potential mode substitution of dockless bike-sharing for other travel modes as a proxy for the real mode substitution, as previous studies did.

Our options for individuals' potential mode substitution behaviors, which comprise (1) mode substitution for walking, (2) mode substitution for private (e-)bikes, (3) mode substitution for public transport, and (4) mode substitution for motorized vehicles (including private car, taxi, motorcycle), are categorical and nonordered. Therefore, we used the multinomial logistic specification (MNL) to examine the association between individual attributes and built environment attributes and their potential mode substitution in response to dockless bike-sharing. We discussed the option "No, I would not make the trip at all" in the descriptive analysis but left it out from the regression analysis, as this option contains a very small number of cases and represents a trip stimulation effect of dockless bike-sharing instead of substitution for other travel modes. Individual attributes include individuals' sociodemographic characteristics, social environment, and travel attitudes, and built environment attributes consider mode accessibility, neighborhood road network and neighborhood satisfaction. Furthermore, to explore whether and to what extent individuals' mode substitution behavior relates to different travel purposes, four MNL models were therefore employed for four travel purposes: 1) work or education commuting, 2) sports and leisure, 3) grocery shopping and 4) recreational activities such as shopping, eating and drinking.

4 Results

4.1 General mode substitution pattern of dockless bike-sharing

Figure 1 demonstrates a comparison of individuals' travel modes potentially substituted by dockless bike-sharing for different trip purposes. For the majority of respondents, dockless bike-sharing was used to potentially substitute for public transport or walking. The substitution rate for motorized transport was limited. Respondents reported using dockless bike-sharing to substitute for private car accounted for 14.80% for grocery shopping trips and only 4.30% for sports and leisure trips. A relatively lower proportion of users potentially substituted dockless bike-sharing for public transit in their trips for sports and leisure purposes (17.30%) compared with trips for commuting (44.60%) and recreational activities (40.30%). The nature of sports and leisure trips might help explain this situation; active travel, such as walking or riding private bicycles, can be more beneficial for individuals to obtain sufficient physical activity or enjoy the environment in their sports and leisure trips. Therefore a large number of travelers may have already adopted other active travel modes before the introduction of dockless bike-sharing in their sports and leisure trips. In addition, there are individuals, though very few, who suggested they would no longer make their trips for sports and leisure and for recreational activities if dockless bike-sharing systems did not exist.

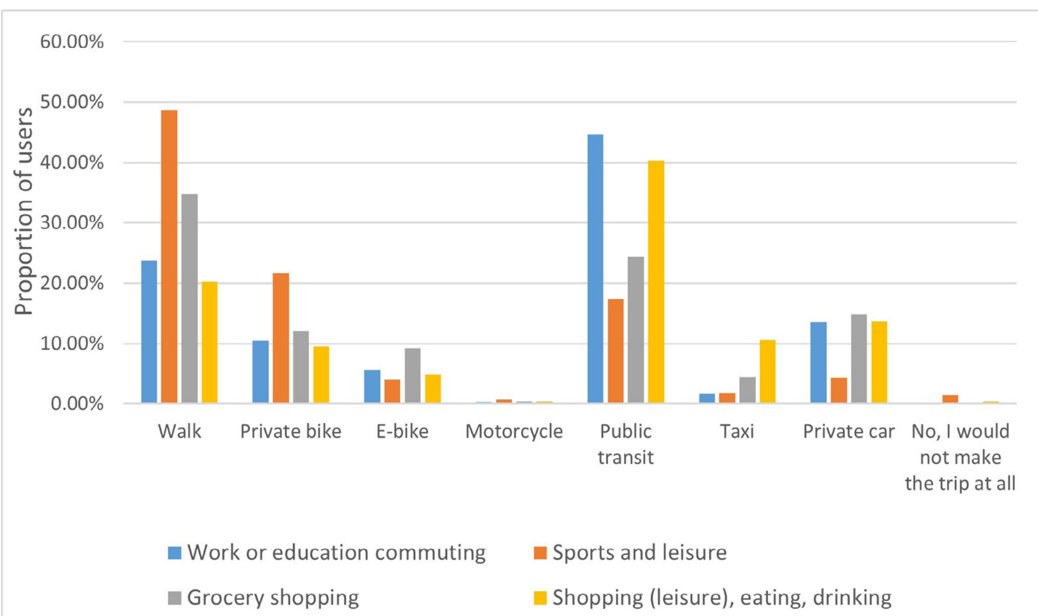

Figure 1. Mode substitution of dockless bike-sharing for different purposes

4.2 Multinomial regression results

The multinomial logistic model was estimated from respondents' mode substitution indicators. There are three categories of potential mode substitution by dockless bike-sharing (private (e-)bike, public transit, and motorized vehicle) and a baseline category: walking. These categories do not have order themselves, but we listed them theoretically on their levels of sustainability from commonly perceived the most sustainable mode to the least sustainable mode. We choose walking as the baseline so that it is easier to see the sustainable meanings underlying the potential mode substitution by dockless bike-sharing, through comparing the likelihood of substituting for a less sustainable mode to the likelihood of substituting for a mode more sustainable than or equal sustainable to dockless bike-sharing. Four regressions (Model 1 for commuting, Model 2 for sports and leisure, Model 3 for grocery shopping, and Model 4 for recreational activities) were estimated. All four models passed the chi-square test of significance that compared the current models (Models 1-4) to their corresponding intercept-only models. Model estimation statistics are shown in Table 3. All models were significant at the given cutoff (p value < 0.05). The four estimated multinomial logistic models resulted in Nagelkerke rho-square values of 0.470, 0.433, 0.482, and 0.457, respectively. Table 3 presents the parameter estimates, that is, the effects of independent variables on potential mode substitution by dockless bike-sharing.

4.2.1 Work or education commuting

The likelihood that individuals use dockless bike-sharing to potentially substitute for various travel modes in their trips of commuting displayed a subtle difference among people with divergent socio-demographics. Age, gender, and employment status did not show significant associations. However, with regard to household income, respondents with lower monthly income had a lower likelihood (odds ratio = 0.212) of potentially substituting dockless bike-sharing for a motorized vehicle on commuting trips. A possible explanation for this finding is that low-income groups have a lower usage rate of cars. Moreover, people living in places provided by employers or in student dormitories were less likely (odds ratio = 0.293) to use dockless bike-sharing to potentially substitute a public transit trip (rather than a walking trip) for their commute to work or school. This result may be explained by commuting distance, as employer-provided housing and student dormitories are often located in neighborhoods near people's work or study places. In addition, respondents in poor or fair self-reported health were more likely to potentially replace car trips by dockless bike-sharing. For psychological determinants, people with a pro-car attitude were found to have higher odds (3.525) of replacing a car trip with dockless bike-sharing, whereas people with a pro-walking attitude were less likely to potentially substitute dockless bike-sharing for motorized vehicles (odds ratio = 0.551) and private (e-)bikes (odds ratio = 0.616) than for walking. Dockless bike-sharing users who have a pro-environment/health attitude had a higher tendency (despite the relatively weak significance) to replace a car trip rather than a walking trip with dockless bike-sharing.

Individuals' mode accessibility was found to exert a direct impact on their potential mode substitution behavior in response to dockless bike-sharing systems. For respondents who possess at least a private e-bike or bicycle, dockless bike-sharing were more likely to potentially substitute for private e-bikes or bicycles compared to walking when traveling for commuting. Car ownership positively influenced the potential substitution of dockless bike-sharing for motorized vehicles in commuting trips (odds ratios = 20.636). The explanation for this result could be that the travel modes to which dockless bike-sharing users have access are closely related to their primary modes of meeting daily travel needs adopted prior to the advent of dockless bike-sharing. Variables related to accessibility to public transit were also investigated. Respondents who live in a neighborhood with higher access to buses were found to be less likely to potentially substitute dockless bike-sharing for public transit than for walking in their commuting trips (odds ratios = 0.896). It is possible that respondents tend to use dockless bike-sharing as a connection to buses for commuting, and those who have a denser bus stop distribution within their living neighborhoods used to complete the "first-/last- mile" trips on foot. Nonetheless, the subjectively measured variable measuring individuals' overall satisfaction with their residential neighborhood, was found to play a significant role only in their potential mode substitution behavior for commuting trips. Respondents who reported being less satisfied with their neighborhood had a higher tendency to use dockless bike-sharing to potentially substitute for private bicycles or e-bikes than for walking (odds ratio = 2.448).

4.2.2 Sports and leisure

The estimation results of Model 2 implied that male users of dockless bike-sharing were more likely (odds ratio = 2.390) to substitute dockless bike-sharing for sports and leisure trips by private (e-)bike rather than walking. In addition, similar to commuting trips, respondents in poor or fair self-reported health had a higher likelihood to potentially substitute for motorized vehicles for sports and leisure purpose by dockless bike-sharing. Nonetheless, other socio-demographical variables, including age, household income, employment and living situation were not found to play a significant role in the mode substitution behaviors in response to dockless bike-sharing systems for sports and leisure purposes. The exploration for social environment suggested that the more social support that users received from their families and friends towards dockless bike-sharing usage, the less likely they were to potentially substitute dockless bike-sharing for motorized vehicles compared with walking in their sports and leisure trips. People with a pro-walking attitude were less likely to potentially substitute dockless bike-sharing for private (e-)bikes than for walking in sports and leisure trips, similar to what we found in Model 1 for commuting trips. However, Model 2 presented different associations between the pro-environment/health and mode substitution behavior for sports and leisure trips compared with Model 1. The results suggested that a pro-environment/health attitude was associated with higher odds (1.834) of potentially replacing private (e-)bike by dockless bike-sharing for sports and leisure trips. These differences could be related to the nature of trips of various purposes, sports and leisure trips tends to receive less temporal and spatial constraints than commuting trips.

Considering the mode accessibility, a higher likelihood of using dockless bike-sharing to potentially substitute for private (e-)bikes was found for respondents who possess at least a private bicycle when traveling for sports and leisure (odds ratio = 5.859) and those who live in a neighborhood with higher access to subways (odds ratio = 2.506). The length of bicycle paths and pedestrian-priority roads within residential neighborhoods was assessed to explore the influence of neighborhood road networks on mode substitution behavior. Models 2 revealed that respondents who live in a neighborhood dominated by bicycle paths had a higher likelihood (odds ratio = 1.395) of potentially replacing public transit trips by dockless bike-sharing for sports and leisure purposes. It is possible that the pleasant and attractive cycling environment of their residential neighborhoods could be one factor driving their choice to become dockless bike-sharing users.

4.2.3 Grocery shopping

Among individuals' sociodemographics, living situation and self-reported health tended to play a role in the mode substitution behavior in response to dockless bike-sharing systems for grocery shopping trips. Respondents living in their privately owned places had a higher likelihood (odds ratio = 3.667) to potentially replace private (e-)bikes by dockless bike-sharing for grocery shopping trips. In addition, dockless bike-sharing users in better self-reported health were found more likely to use dockless bike-sharing to potentially substitute for private (e-)bikes instead of walking for their grocery shopping trips. For travel-related attitudes, pro-car dockless bike-sharing users appeared to have a higher likelihood to potentially replace private (e-)bikes and motorized vehicles than to replace walking by dockless bike-sharing systems (odds ratios: 2.053 and 2.128, respectively). A similar positive result held for the association between a pro-e-bike/e-scooter attitude and higher odds of potentially substituting for private (e-)bikes rather than for walking by dockless bike-sharing (odds ratio: 1.729).

The objectively measured neighborhood spatial attributes exerted an important influence on mode substitution behavior for grocery shopping trips. For respondents who possess at least a private e-bike or bicycle, dockless bike-sharing systems were more likely to potentially substitute for private (e-)bikes compared to walking. Car ownership and bicycle ownership also positively influenced the potential substitution for motorized vehicles for grocery shopping trips (odds ratios: 7.527 and 2.494, respectively). With regard to variables related to accessibility to public transit, neighborhood with higher access to buses were associated with a lower likelihood to potentially substitute dockless bike-sharing for public transit than for walking in respondents' grocery shopping trips (odds ratios = 0.810). This association is similar to what we found in Model 1 for work or education commuting travel. In addition, a higher number of subway stations within the residential neighborhood was associated with a higher likelihood to potentially replace public transit by dockless bike-sharing systems for grocery shopping trips (odds ratio = 2.370). Among four different travel purposes, the road network of residential neighborhood only showed a significant influence on potentially substituting dockless bikes-sharing for motorized vehicles for grocery shopping trips. Respondents who live in a neighborhood dominated by bicycle paths had a higher likelihood of potentially substituting dockless bike-sharing for motorized vehicles (odds ratio = 1.502) and also public transit (odds ratio = 1.324), while those who live in a neighborhood with higher proportions of pedestrian-priority roads tended to have lower odds to potentially replace motorized vehicles than replace walking by dockless bike-sharing.

4.2.4 Recreational activities: shopping (leisure), eating, drinking

The mode substitution behavior in trips for recreational activities were found to be most influenced by travel-related attitudinal factors. Our examination of individuals' socio-demographics in Model 4 only disclosed that older dockless bike-sharing respondents had significant lower odds (0.939) of potentially substituting dockless bike-sharing for public transit in their trips for recreational activities. The influence of travel attitude displayed similar results as on the mode substitution for grocery shopping trips. Having a pro-car attitude, a pro-e-bike/e-scooter attitude, or a pro-bicycle attitude were associated with higher odds to potentially substitute dockless bike-sharing for private e-bikes or bicycles than for walking (odds ratios: 2.765, 1.762, and 3.112, respectively). Pro-car dockless bike-sharing users also showed a higher likelihood (odds ratio = 2.475) to potentially use dockless bike-sharing as a substitution for motorized vehicles for trips of recreational activities.

Like the socio-demographics, residential neighborhood attributes did not play an important part for mode substitution behavior in the trips of recreational activities. It is possible that individuals tend to go to commercial centers to pursue recreational activities such as recreational shopping, eating and drinking, hence these trips could usually exceed or take place outside the residential neighborhoods. One exception is the e-bike ownership, for respondents who possess at least a private e-bike in their household, dockless bike-sharing were more likely to substitute for private e-bikes or bicycles than for walking (odds ratio = 3.711).

Table 3. Parameter estimates and significance, mode substitution behavior

	Model 1 Commuting			**Model 2 Sports and leisure**			**Model 3 Grocery shopping**			**Model 4 Recreational activities**		
Mode substitution (reference category = walking)	Private (e-)bike	Public transit	Motorized vehicle	Private (e-)bike	Public transit	Motorized vehicle	Private (e-)bike	Public transit	Motorized vehicle	Private (e-)bike	Public transit	Motorized vehicle
	Odds ratio			Odds ratio			Odds ratio			Odds ratio		
(Intercept)												
Individual attributes												
Age	1.024	1.004	1.047	0.993	0.978	1.054	0.991	**0.940.**	1.016	0.969	**0.939***	0.972
Gender												
Female (base)	.	.	.	.	.	.	.	.	.	.	.	.
Male	1.182	1.252	1.448	**2.390***	1.842	1.130	0.672	1.167	0.733	0.861	0.916	**0.468.**
Household income												
Low income	0.622	0.845	**0.212***	2.267	0.493	0.379	1.766	1.196	1.441	2.539	1.073	1.360
Median income	0.729	1.112	1.356	1.769	1.111	0.836	**0.380.**	1.458	1.059	0.450	0.708	0.556
High income (base)	.	.	.	.	.	.	.	.	.	.	.	.
Employment												
Part-time employment, students, etc.	2.061	0.850	0.663	0.699	0.570	2.968	0.871	0.825	0.434	1.679	1.648	0.582
Full-time employment (base)	.	.	.	.	.	.	.	.	.	.	.	.
Living situation												
Privately owned	0.573	0.664	1.769	1.358	1.058	1.520	**3.667***	0.685	**2.887.**	2.333	0.902	1.494
Employers' offer/student dormitory	**0.285.**	**0.293***	0.226	0.636	1.818	0.803	0.391	0.705	1.551	0.170	0.652	0.498
Others (base)	.	.	.	.	.	.	.	.	.	.	.	.
Self-reported health												
Fair and below	1.501	0.839	**2.645.**	1.068	1.639	**3.991.**	**0.273***	0.713	0.459	0.344	0.925	0.579
Good	1.382	1.377	1.207	0.524	1.255	0.781	**0.119****	0.953	**0.328***	**0.331.**	0.838	0.482
Very good and above (base)	.	.	.	.	.	.	.	.	.	.	.	.
Social environment	1.399	1.144	1.663	0.698	0.738	**0.256***	1.130	1.599	0.771	1.299	0.937	1.161
Travel attitude												
Pro-car	1.285	1.177	**3.525****	1.266	0.816	0.895	**2.053****	1.391	**2.128****	**2.765****	1.264	**2.475****
Pro-e-bike/e-scooter	0.941	0.781	1.285	1.124	0.975	0.742	**1.729***	0.948	1.113	**1.762***	0.951	1.433
Pro-PT	0.994	1.091	**0.455****	0.854	1.025	1.284	1.019	1.323	1.487	1.084	1.219	0.791

	Model 1 Commuting			**Model 2 Sports and leisure**			**Model 3 Grocery shopping**			**Model 4 Recreational activities**		
Mode substitution (reference category = walking)	Private (e-)bike	Public transit	Motorized vehicle	Private (e-)bike	Public transit	Motorized vehicle	Private (e-)bike	Public transit	Motorized vehicle	Private (e-)bike	Public transit	Motorized vehicle
	Odds ratio			Odds ratio			Odds ratio			Odds ratio		
Pro-bicycle	1.550	0.930	0.764	1.490	1.117	1.349	1.336	0.964	1.174	**3.112****	1.381	1.471
Pro-walking	**0.616***	0.824	**0.551****	**0.525****	0.886	1.833	**0.660.**	0.864	1.188	**0.482***	**0.689.**	0.666
Pro-environment/health	1.304	1.203	**1.566**.	**1.834***	1.014	0.898	1.161	0.868	1.147	1.067	0.895	0.846
Anti-PT	**0.708.**	0.921	1.193	0.999	0.720	0.825	1.190	1.102	1.359	1.206	0.954	0.782
Anti-travel	1.086	1.177	0.816	0.838	**0.675***	0.814	1.041	0.988	0.733	1.308	0.820	0.864
Spatial variables												
Mode accessibility												
Car ownership: no	.	.	.	.	.	.	.	.	.	.	.	.
Car ownership: yes	0.713	0.849	**20.636***	1.303	1.663	2.680	0.875	0.663	**7.527****	0.621	1.479	2.633
Motorcycle ownership: no	.	.	.	.	.	.	.	.	.	.	.	.
Motorcycle ownership: yes	1.591	0.953	0.986	1.421	1.740	**5.727.**	0.587	1.077	0.863	2.163	1.075	1.628
E-bike ownership: no	.	.	.	.	.	.	.	.	.	.	.	.
E-bike ownership: yes	**2.407.**	1.049	0.971	1.784	0.692	0.581	**2.911***	0.870	0.735	**3.711***	1.147	1.334
Bicycle ownership: no	.	.	.	.	.	.	.	.	.	.	.	.
Bicycle ownership: yes	**4.178****	**1.746.**	1.265	**5.859****	0.643	1.767	**3.474****	1.517	**2.494***	1.977	1.167	0.890
Number of bus stops	0.968	**0.896***	0.881	0.930	0.948	1.044	0.928	**0.810****	0.967	1.015	0.961	0.881
Number of subway stops	1.035	1.352	1.256	**2.506***	1.154	0.706	1.005	**2.370***	1.728	0.756	1.789	1.199
Road network												
The length of bicycle paths	0.985	1.129	0.926	0.961	**1.395***	1.034	1.136	**1.324***	**1.502***	1.025	1.115	1.022
The length of pedestrian-priority roads	0.968	**0.807***	0.921	**1.185.**	0.802	0.945	0.982	0.856	**0.572****	1.137	1.067	1.095
Neighborhood satisfaction												
Neutral and below	**2.448***	1.689	0.817	0.987	0.537	2.133	1.882	1.271	1.190	**2.628**.	1.485	**2.448.**
Satisfied and above (base)	.	.	.	.	.	.	.	.	.	.	.	.
Model statistics												
Number of observations	354			273			250			262		
-2 log likelihood												
Null model	909.590			649.523			679.887			689.186		
Estimated model	708.086			513.376			530.181			544.440		
Chi-Square (df)	**201.504 (81) ****			**136.147(81)****			**149.706 (81) ****			**144.746 (81) ****		
Nagelkerke rho-square	0.470			0.433			0.482			0.457		

“. ” Significant at 0.1; “*” Significant at 0.05; “**” Significant at 0.01.

5 Discussion

Dockless bike-sharing is experiencing rapid growth in popularity worldwide. As a new generation of bike-sharing and thereby also a new travel option, dockless bike-sharing has the potential to exert an influence in urban mobility by substituting walking, public transit, or motorized transport (such as cars, taxis, motorcycles) trips. Using survey data collected from residents in Beijing and geodata on land use and public transit, this study conducted multinomial logistic regressions to explore the potential mode substitution behavior influenced by dockless bike-sharing for four different travel purposes: work or education commuting, sports and leisure, grocery shopping, and recreational activities such as shopping, eating and drinking. The majority of respondents were found to potentially substitute dockless bike-sharing systems for walking or public transit. The finding that dockless bike-sharing attracted users largely from public transit and walking is largely consistent with previous findings concerning docked bike-sharing research (e.g., Fishman et al., 2015; Kong et al., 2020). We also found that dockless bike-sharing systems could potentially help reduce car usage, although to a limited extent, consistent with the findings of Ma et al. (2019). In addition to the mode substitution effects, new trips can be generated in the context of dockless bike-sharing usage. Our study revealed that dockless bike-sharing systems had the potential to stimulate new trips for sports and leisure and for recreational activities, but to a limited extent.

The analysis of dockless bike-sharing users in Beijing indicated individual-level discrepancies in the potential mode substitution behavior in response to dockless bike-sharing systems. Sociodemographics including age, gender, household income, living situation and health status were found to play different roles in the mode substitution for walking, private (e-)bike, public transit, and motorized vehicle. Similar to other researchers' work on docked bike-sharing claiming an association between age and mode substitution (e.g., Barbour et al., 2019), our study revealed that younger dockless bike-sharing respondents had a higher likelihood of potentially replacing public transit trips for recreational activities by dockless bike-sharing. No significant association between gender and mode substitution of dockless bike-sharing for public transit was found, different from Shaheen et al. (2013) docked bike-sharing study suggesting that being male is a common feature across several cities in North America associated with mode shifting from public transit to docked bike-sharing. However, male dockless bike-sharing users in our study reported a higher propensity to potentially substitute dockless bike-sharing for private (e-)bikes rather than for walking when taking sports and leisure trips. In addition, individuals' household income and living situation could both make a significant difference in the substitution of dockless bike-sharing for commuting trips. Respondents with lower household income had a lower likelihood of potentially substituting dockless bike-sharing for motorized vehicles. This finding differs from what Barbour et al. (2019) suggested in their research that high-income households are less likely to increase their auto-usage but more likely to switch to another mode of active transportation in the absence of docked bike-sharing.

Travel attitudes were confirmed in the results to express an explanatory power in capturing dockless bike-sharing users' mode substitution behavior. In work or education commuting trips, for example, people with a pro-car attitude were more likely to potentially replace motorized vehicles instead of walking by dockless bike-sharing, whereas people with a pro-walking attitude were less likely to potentially substitute dockless bike-sharing for motorized vehicles and private (e-)bikes than for walking. These findings suggest that individuals' preferences and attitudes towards available travel mode options play a critical role in the potential substitution behavior for other travel modes in response to dockless bike-sharing systems. Prior studies have already confirmed the importance of travel attitude when analyzing the participation and utilization of bike-sharing systems (Chen et al., 2020b; Damant-Sirois & El-Geneidy, 2015; Fernández-Heredia et al., 2014). Our study extended the role of travel attitude from the usage of dockless bike-sharing to the mode substitution in response to dockless bike-sharing, thus contributing to the limited number of empirical studies on the psychological determinants of potential mode substitution behavior by dockless bike-sharing systems. In addition, from our analysis of travel attitude, positive associations between individuals with positive attitudes towards varying modes (such as a pro-car or a pro-e-bike/e-scooter attitude) and the likelihood of using dockless bike-sharing to potentially substitute for the corresponding modes were reported. It seems that dockless bike-sharing systems attract not only bicycle lovers but also users with a preference for other travel modes.

Our research included the assessment of mode accessibility in neighborhood environment characteristics. The availability of private e-bikes or bicycles and cars was positively associated with the potential substitution for private (e-)bikes and motorized vehicles by dockless bike-sharing when traveling for various purposes, such as commuting, sports and leisure. This finding could suggest that, even for individuals with good accessibility to different travel modes, dockess bike-sharing systems can still be competitive in replacing other travel modes to meet their daily travel needs. Our findings indicated a propensity of people who have a denser bus stop distribution within their living neighborhood to potentially substitute dockless bike-sharing for walking rather than for public transit in their commuting and grocery shopping trips, which reflects the potential of dockless bike-sharing as a complement (for relatively longer distance) or substitution (for shorter distance) for walking in “first-/last-mile” trips. The positive association between the length of bicycle paths and the likelihood of potentially replacing public transit or motorized vehicles by dockless bike-sharing suggested that the cycling infrastructure of residential neighborhood could be an important facilitator for users of public transit and motorized vehicles to switch to dockless bike-sharing systems. Prior studies have already claimed that a cycling-friendly and attractive residential neighborhood environment can encourage the adaptation of bike-sharing usage among individuals (Buck & Buehler, 2012; Rixey, 2013).

Previous studies investigating the mode substitution behavior of bike-sharing systems have generally treated different travel purposes as a homogenous group or focused simply on commuting trips (e.g., Campbell & Brakewood, 2017; Ma et al., 2020; Zhu et al., 2013). However, our findings suggest that the impacts of individual attributes and neighborhood environment on potential mode substitution behavior of dockless bike-sharing vary across different travel purposes. The influence of travel attitudes tends to display similar results in regard to potential mode substitution behavior in trips for grocery shopping and recreational activities, yet distinct from the results for commuting or sports and leisure trips. For instance, the potential mode substitution for private (e-)bikes by dockless bike-sharing in trips for recreational activities was more significantly influenced by individuals’ attitudes towards car, e-bike, bicycle, and walking. However, for commuting trips, individuals’ attitudes towards various travel modes tended to play a more significant role in their potential substitution for motorized vehicles by dockless bike-sharing. On the other hand, for neighborhood environment variables, the association with potential mode substitution behavior by dockless bike-sharing demonstrates a comparable pattern between travel purposes of work or education commuting and grocery shopping. And different from trips of three other purposes, residential neighborhood attributes did not play an important part for the mode substitution behavior in the trips for recreational activities. These results suggest that the nature of trips with different travel purposes also influences mode substitution in response to dockless bike-sharing as well as its determinants. Consistent with what Shaheen et al. (2013) proposed, it is important to distinguish between commuting trips, utility-oriented trips and leisure travel purposes when assessing bike-sharing mode substitution.

However, this study is subject to several limitations. First, given the available data, there is limited information about the trip details, such as the travel distance or travel time, for different purposes. Future studies could consider collecting more detailed trip data to help explain the heterogeneity of potential mode substitution and its determinants in response to dockless bike-sharing. Second, this study evaluated the neighborhood environment by mode accessibility, road networks and neighborhood satisfaction, while other spatial variables, such as population density and land-use mix, were not assessed due to data availability. Future studies could explore these variables for additional insights. Third, our study used a survey question of hypothetical travel mode choice if dockless bike-sharing systems did not exist, to evaluate the potential mode substitution behavior by dockless bike-sharing systems as a proxy for the real mode substitution behavior. Nonetheless, the hypothetical travel mode choice if dockless bike-sharing did not exist ("alternative mode") is not always consistent with the reported travel mode prior to dockless bike-sharing adoption ("previous mode") (Bigazzi & Wong, 2020), as people may not always revert to their previous behavior. Future studies could consider conducting a longitudinal study including surveys before and after the appearance of dockless bike-sharing to obtain accurate data about dockless bike-sharing users' travel modes prior to dockless bike-sharing adoption. Four, our study applied the MNL models to explore the influence of individual and spatial attributes on potential mode substitution in the absence of dockless bike-sharing, future research could consider nested logit model to test different nested structures for mode substitution options.

The encouragement of sustainable travel in many regions and wide-scale adoption of dockless bike-sharing systems have increasingly made them an integral aspect of many individuals' daily travel options. Our investigation on the impact of dockless bike-sharing on mode substitution provides an approach for local planners to understand how dockless bike-sharing is positioned in the urban transport system, whether and what changes it has brought to the urban mobility landscape. Due to the fact that dockless bike-sharing tends to mostly substitute for public transit and walking, we recommend that policy makers consider improving the connection between dockless bike-sharing and public transit, both physically by designating geofenced parking areas for bicycles surrounding public transport stations, and technically by integrating payment systems (e.g., lower pricing schemes). In addition, decision makers could also consider the improvement of cycling and parking infrastructure alongside the public transit stations and residential neighborhoods to attract more individuals of other travel modes into dockless bike-sharing. The findings of the current study can provide empirical support for policy makers to understand the individual and spatial characteristics that influence users to substitute car, public transit and walking trips with dockless bike-sharing.

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